CANADIAN AERONAUTICS AND SPACE INSTITUTE

FIFTH CANADIAN SYMPOSIUM ON AIR CUSHION TECHNOLOGY

OTTAWA: 30th/31st AUGUST - 1st SEPTEMBER 1971

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77 Metcalfe Street
Ottawa, Canada.

PAPER No. 71/5
Price: Members $1.25
Others $2.00

OPTIMIZATION OF THE PERFORMANCE OF AIR CUSHION-SURFACE CONTACTING HYBRID VEHICLES

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SUMMARY The unique ability of the air cushion vehicle to travel over a variety of disparate surfaces has attracted growing attention in off-road transportation industry. Although fully air cushion supported vehicles can function over land, experience to date indicates that ground contact for positioning and control is required for continuous over land operation. One solution is an air cushion-surface contacting hybrid vehicle.

This paper attempts to provide an analytical basis for evaluating and optimizing the performance and design of the hybrid vehicle. The basic power requirements of this type of vehicle are first analyzed and compared with those of the fully air cushion supported vehicle. The approaches to minimizing the power consumption and to improving the economics of the hybrid vehicle are then investigated. Finally, an analytical approach to evaluating and predicting the controllability and mobility of this kind of vehicle is discussed.

INTRODUCTION In the past decade substantial research effort has resulted in the successful development of a series of air cushion vehicles. They have found wide applications in over water operation.

The unique ability of the air cushion vehicle to travel over a variety of disparate surfaces has also attracted growing attention in off-road transportation industry. It appears to offer solutions to a wide range of cross-country transportation problems (1-6).

Although fully air cushion supported vehicles can function over land, experience to date indicates that ground contact for positioning and control is required for continuous over land operation, and that the operating costs of these vehicles are comparatively high. One solution is an air cushion-surface contacting hybrid vehicle.

The feasibility of the hybrid vehicle concept has been demonstrated by the Bertin Terraplane BC7, Vickers-Armstrong Hovertruck, etc. However, the operating performance, capabilities and limitations of this type of vehicle have not been investigated in a systematic way.

This paper attempts to provide an analytical basis for evaluating and optimizing the performance and design of the air cushion-surface contacting vehicle for over land operation.

OPTIMIZATION OF POWER REQUIREMENTS OF THE HYBRID VEHICLE In order to be able to optimize power requirements and to reduce the operating costs of the hybrid vehicle, it is necessary first of all to analyze its basic power consumption. Since the weight of the hybrid vehicle is partly supported by the air cushion and partly by the ground contacting device, such as wheels, the total basic power consumption P_t is given by

$$P_t = P_\ell + P_m + P_a + P_r \tag{1}$$

where
- P_ℓ - power for lift
- P_m - power required to overcome momentum drag
- P_a - power required to overcome profile or aerodynamic drag
- P_r - power required to overcome the motion resistance of the surface contacting gear

All the internal losses of the vehicle are not included in this general analysis, since it is difficult to assess them without referring to a specific design.

(1) Power required to generate aerostatic lift. The power for lift depends on the type of air cushion system and design parameters of the vehicle. Among the air cushion systems currently employed on commercially available vehicles, the Bertin multiple cone skirt may be particularly suited to over land applications (4) (6). The Bertin system is relatively simple, and is the least sensitive to catastrophic lift loss over ditches. Furthermore this system can provide sufficient stability and suitable suspension stiffness. It should be pointed out, however, that power requirements of this system are high. In order to reduce the power consumption, an outer peripheral skirt is used in current designs (6). Based on the assumptions of inviscid incompressible flow, the power required to generate aerostatic lift for a multiple cone system with an outer peripheral skirt is given by

$$P_\ell = h_1 \ell_1 D_{c1} \left(\frac{2\alpha}{\rho}\right)^{\frac{1}{2}} \left(\frac{W_a}{\alpha S_1 + S_2}\right)^{3/2} = C_1 W_a^{3/2} \tag{2}$$

where
- h_1 - hover height
- ℓ_1 - circumference of the outer peripheral skirt
- D_{c1} - discharge coefficient of the outer peripheral skirt
- ρ - air density
- S_1 - cushion area between the outer skirt and the cones
- S_2 - total cushion area of the cones
- W_a - weight supported by the air cushion

α represents the ratio of the cushion pressure between the outer skirt and the cones to that beneath the cones. If both the cones and the outer skirt have the same clearance height and identical discharge coefficient, the ratio α may be determined by

$$\alpha = \frac{n_c^2 \, \ell_2^2}{n_c^2 \, \ell_2^2 + \ell_1^2} \qquad (3)$$

where n_c - number of cones

ℓ_2 - total circumference of the cones

(2) Momentum drag and aerodynamic drag. Power required to overcome momentum drag for a multiple cone system with an outer peripheral skirt may be determined by

$$P_m = \rho \, h_1 \, \ell_1 \, D_{cl} \left[\frac{2 \, \alpha W_a}{\rho \, (\alpha S_1 + S_2)} \right]^{\frac{1}{2}} V^2$$

$$= C_2 \, V^2 \, W_a^{\frac{1}{2}} \qquad (4)$$

in which V is the vehicle speed. Power required to overcome aerodynamic or profile drag is given by

$$P_a = C_a \, A \, V^3 = C_3 \, V^3 \qquad (5)$$

where C_a - coefficient of aerodynamic drag

A - frontal area of the vehicle

(3) Motion resistance of ground contacting gear on unprepared terrain. The study of the general relationship between the performance of an off-road vehicle and its physical environment (the terrain) has attracted considerable attention in cross-country transportation industry, and has been developed quite rapidly in recent years. This branch of applied mechanics has been given the name "Terramechanics".

One of the general approaches to predicting the performance of vehicle running gear on unprepared terrain was developed by Bekker (9) (10) (11). Recently, important contributions to this subject have also been made (12) (13).

The Bekker theory for the motion resistance of various forms of vehicle running gear is based on the assumption that the work expended on motion resistance equals that done in making a rut. Since the pneumatic tire is likely to be the basic type of surface contacting gear for the hybrid vehicle, its behaviour and the prediction of its motion resistance will be briefly reviewed.

If the terrain is sufficiently soft, and the sum of the inflation pressure p_i and the pressure produced by the stiffness of the tire carcasses p_{ca} is

larger than a critical value p_{cr}, which the ground can support at the lowest point of the tire circumference, the tire will remain round like a rigid rim. The critical pressure p_{cr} is given by

$$p_{cr} = \left(\frac{K_c}{b} + K_\varphi\right)^{\frac{1}{2n+1}} \left[\frac{3\ W_w}{(3-n)\ b\ \sqrt{D}}\right]^{\frac{2n}{2n+1}} \tag{6}$$

where K_c, K_φ and n - measured terrain describing constants

b, D - tire width and diameter respectively

W_w - tire load

The motion resistance of the rigid wheel R_{r1} is determined by

$$R_{r1} = \frac{1}{(3-n)^{\frac{2n+2}{2n+1}}\ (n+1)\ (K_c + b\ K_\varphi)^{\frac{1}{2n+1}}} \left[\frac{3\ W_w}{\sqrt{D}}\right]^{\frac{2n+2}{2n+1}}$$

$$= C_4\ W_w^{\frac{2n+2}{2n+1}} \tag{7}$$

If $p_i + p_{ca} \leqslant p_{cr}$, the tire will be flattened along a portion of the circumference, and its motion resistance is given by

$$R_{r2} = \frac{\left[b\ (p_i + p_{ca})\right]^{\frac{n+1}{n}}}{(K_c + b\ K_\varphi)^{\frac{1}{n}}\ (n+1)} \tag{8}$$

In off-road operation, quite often the ground is sufficiently soft and the tire behaves like a rigid rim, the motion resistance of a vehicle with N tires R_r is given by

$$R_r = \frac{C_4}{N^{\frac{1}{2n+1}}}\ (N\ W_w)^{\frac{2n+2}{2n+1}}$$

$$= C_5\ W_w^{\frac{2n+2}{2n+1}} \tag{9}$$

in which W_r is the vehicle weight supported by the tires.

The power required to overcome the motion resistance of the wheels is determined by

$$P_r = C_5 \; V \; W_r^{\frac{2n+2}{2n+1}} \tag{10}$$

Based on the above analysis, the basic power consumption of the hybrid vehicle with an outer peripheral skirt and with wheels as surface contacting device is given by

$$P_t = C_1 \; W_a^{3/2} + C_2 \; V^2 \; W_a^{\frac{1}{2}} + C_3 \; V^3 + C_5 \; V \; W_r^{\frac{2n+2}{2n+1}} \tag{11}$$

Introducing the load distribution ratio β, which is the ratio of the load supported by the air cushion W_a to the total weight of the vehicle W, equation (11) may be rewritten as

$$P_t = C_1 \; W^{3/2} \; \beta^{3/2} + C_2 \; V^2 \; W^{\frac{1}{2}} \; \beta^{\frac{1}{2}} + C_3 \; V^3$$

$$+ \; C_5 \; V \; W^{\frac{2n+2}{2n+1}} \; (1 - \beta)^{\frac{2n+2}{2n+1}} \tag{12}$$

It can be seen that other conditions being equal, the basic power consumption of the hybrid vehicle is a function of the load distribution between the air cushion and the surface contacting gear. From equation (12), it is clear that for a given vehicle at a particular operating condition, there is an optimum load distribution which minimizes the basic power consumption. In order to find the optimum load distribution, the first partial derivative of P_t with respect to β is taken and set equal to zero.

$$\frac{\partial P_t}{\partial \beta} = \frac{3}{2} \; C_1 \; W^{3/2} \; \beta^{\frac{1}{2}} + \frac{1}{2} \; C_2 \; V^2 \; W^{\frac{1}{2}} \; \beta^{-\frac{1}{2}} - \frac{2n+2}{2n+1} \; C_5 \; V \; W^{\frac{2n+2}{2n+1}} \; \beta^{\frac{1}{2n+1}} = 0 \tag{13}$$

Figure 1 illustrates the variation of the optimum load distribution ratio β_{opt} with terrain parameter $\frac{K_c}{b} + K_\varphi$ for a hybrid vehicle with an outer peripheral skirt. The parameters of the vehicle used in the calculation are given in the Appendix.

The diagram clearly illustrates the conditions under which the use of the combination of air cushion and wheels to support the vehicle weight (hybrid operation mode) is most advantageous from the point of view of power consumption. For instance, as shown in Figure 1, in sandy loam or clayey loam the optimum performance may be achieved in the hybrid operation mode. On the other hand, in compacted sand the use of air cushion seems to be quite unnecessary, while in muskeg and the like, a significant portion of the vehicle weight should be supported by the air cushion.

It is also interesting to note that for a given hybrid vehicle, the optimum value of load distribution ratio undergoes a drastic change at a particular terrain condition. This is mainly due to the fact that when the firmness of ground is above a certain level, the pneumatic tire ceases to behave like a rigid wheel and flattens along a portion of its circumference as mentioned previously. This limits the sinkage of the tire and hence the motion resistance.

PROPULSION AND CONTROL OF THE HYBRID VEHICLE The effectiveness of ground propulsion system can be assessed by the maximum tractive effort that can be developed. By application of the principles of soil (or snow) mechanics, the maximum tractive effort of an undeformed tire H_w is given by

$$H_w = b\ r \sin \theta_o\ c + W_w \tan \varphi \qquad (13)$$

where r - tire radius

θ_o - contact angle

c - cohesion of the soil (or snow)

φ - angle of internal shearing resistance of the soil (or snow)

As an example, Figure 2 illustrates the variation of the maximum tractive effort and total drags with load distribution for a hybrid vehicle in snow. The parameters of the vehicle used in the calculation are the same as those used for Figure 1.

After investigating a number of off-road operating conditions ranging from muskeg through clay to compacted sand, it appears that in order to provide the hybrid vehicle with adequate off-road mobility, an auxiliary air propulsion system is needed. A fan air propulsion system integrated with the lift system seems to offer a simple solution.

The effectiveness of the ground contacting gear as yaw and sideways control device for a hybrid vehicle depends on the cornering force that can be developed. Recent investigations by Schwanghart provided useful insights into the prediction of cornering force developed by a tire on deformable surface (14). Generally speaking, the cornering force consists of two components:

(1) Lateral shearing forcing on the contact area F_s. For an undeformed tire on unprepared terrain, lateral shearing force is given by

$$F_s = b\ r\ \theta_o\ c + W_w \tan \varphi \qquad (14)$$

(2) Lateral force resulting from the normal pressure exerted on the side wall of the tire F_b. This force is similar in nature to that acting on a retaining wall and can be predicted by the retaining wall theory of soil mechanics (15) (16).

$$F_b = 2 \gamma N_\gamma \cos \delta \left[r^2 \ell - \frac{\ell^3}{3} + (r - z_o) r^2 \theta_o \right]$$

$$+ c N_c \cos \delta \left[r^2 \theta_o - \ell (r - z_o) \right] \qquad (15)$$

where γ - soil (snow) density

N_γ, N_c - dimensionless soil (snow) factors from reference (16)

ℓ - contact length of the wheel

z_o - rut depth

δ - angle of interface friction between the side wall of tire and soil

As an example, Figure 3 shows the variation of the maximum lateral acceleration A_s that can be sustained under a steady turn with load distribution for a hybrid vehicle in snow. The parameters of the vehicle used in the calculation are the same as those used for Figure 1. The lateral acceleration shown is calculated from the cornering force that can be developed by the tires of the vehicle. The possible minimum turning radius of the vehicle at forward speed of 10 mph is also plotted in the same figure.

After analyzing a number of off-road operating conditions ranging from snow through clay to loose sand, it appears to confirm that the use of wheels as yaw and sideways control device for the air cushion vehicle is quite effective, even on soft ground.

CONCLUSIONS The results of the analysis appear to confirm the merits of the air cushion-surface contacting hybrid vehicle concept. It offers a greater degree of mobility over many types of terrain than the conventional wheeled vehicle , while it provides better controllability and manoeuvrability than the fully air cushion supported vehicle. The optimum operating performance and economy of operation may be achieved by proper design. It is found that among other design parameters, the load distribution between the air cushion and the ground contacting gear of a hybrid vehicle has considerable effect on its power consumption. For a given vehicle in a particular type of terrain, there is an optimum load distribution which minimizes the power consumption.

It is shown that the use of wheels as yaw control device for the hybrid vehicle is quite effective, even on soft terrain. It is also shown that wheeled propulsion has limitations in cross-country operation. In order to provide the hybrid vehicle with adequate off-road mobility, an auxiliary air propulsion system appears to be needed. A fan air propulsion system integrated with the lift system seems to offer a simple solution.

APPENDIX Parameters of the air cushion-surface contacting vehicle used in the analysis:

Vehicle weight W	11000 lb

Parameters of the multiple cone system with an outer peripheral skirt:

number of cones n_c	8
circumference of the outer peripheral skirt ℓ_1	57.5 ft
circumference of the cone ℓ_2	11.8 ft
cushion area between the cones and the outer skirt S_1	103.1 ft^2
total cushion area of the cones S_2	88.4 ft^2
discharge coefficient $D_{c1}=D_{c2}$	0.63

Ground contacting gear:

four 13.00 - 24 tires; inflation pressure p_i = 18 psi;

pressure produced by the stiffness of the tire carcasses p_{ca} = 4 psi.

Frontal area of the vehicle 98.3 ft^2

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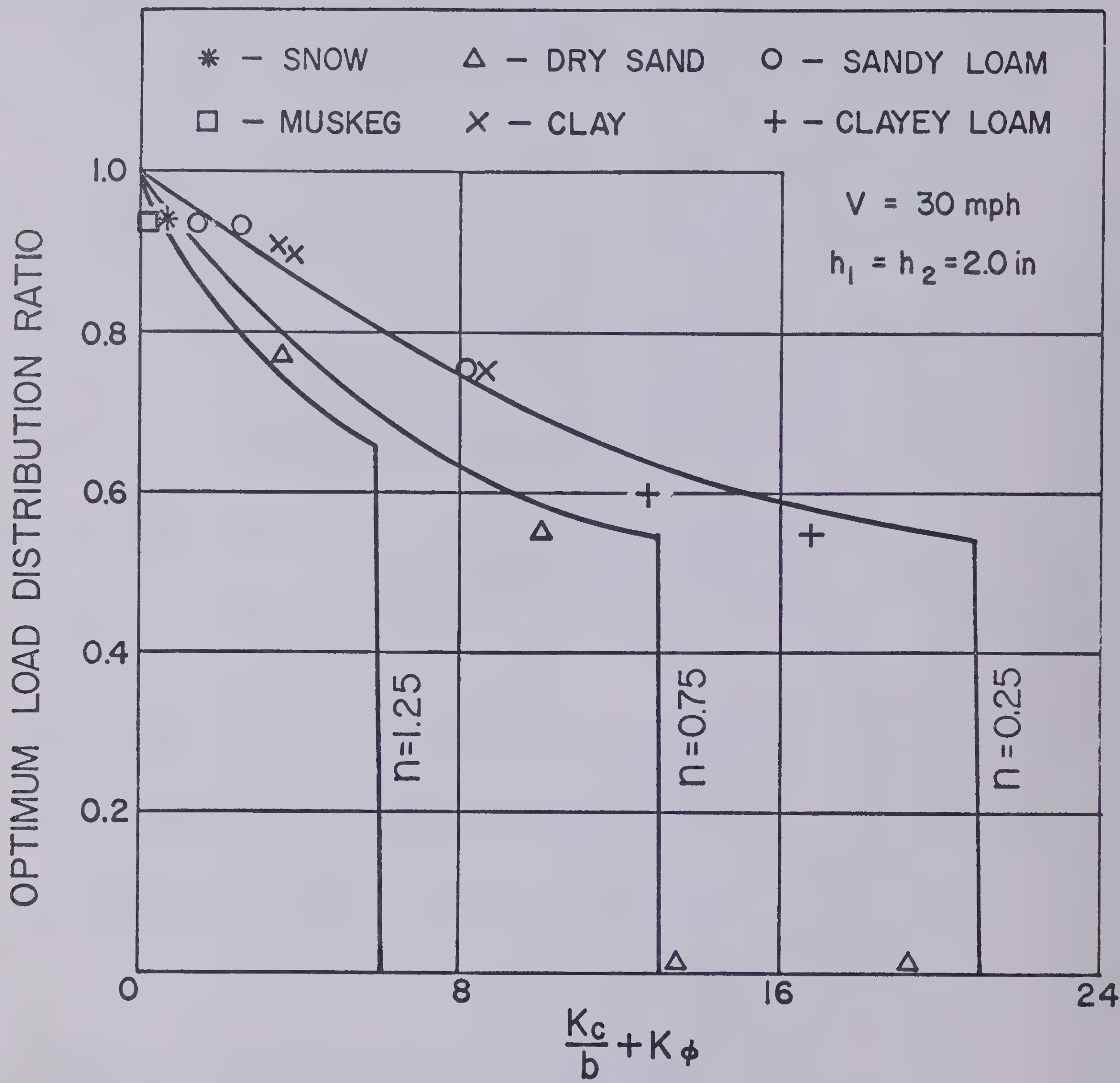

Figure 1 Variation of the optimum load distribution with terrain conditions for a hybrid vehicle with an outer peripheral skirt operating at a hoverheight of 2.0 in. and at a speed of 30 mph.

(terrain data shown are from references (10) and (11))

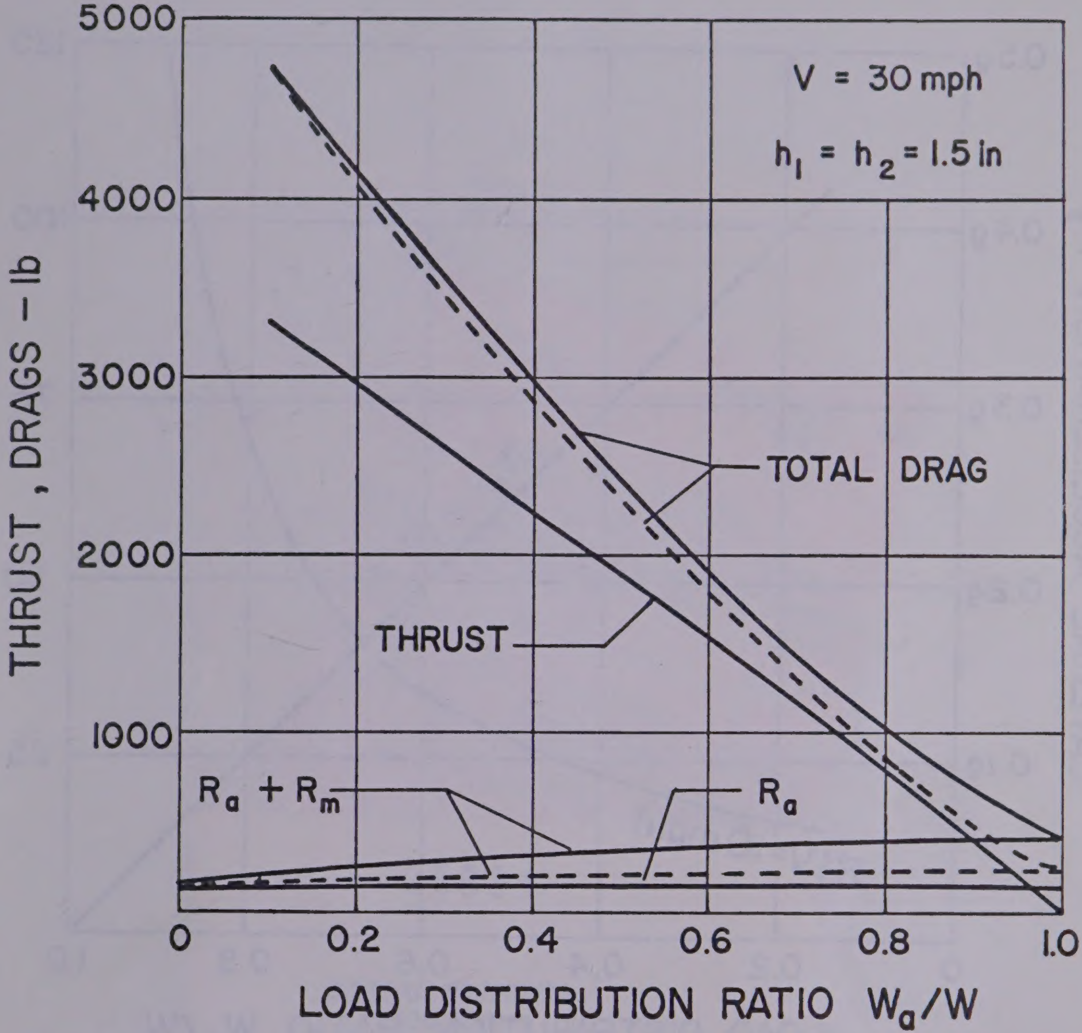

Figure 2 Variation of thrust and drags with load distribution of a hybrid vehicle in snow ($n = 1.0$, $K_c = 3.6$, $K_\varphi = 0.3$, $c = 0.1$ psi, $\varphi = 18^o$)

—— basic multiple cone system

---- multiple cone system with an outer peripheral skirt

R_a - aerodynamic drag

R_m - momentum drag

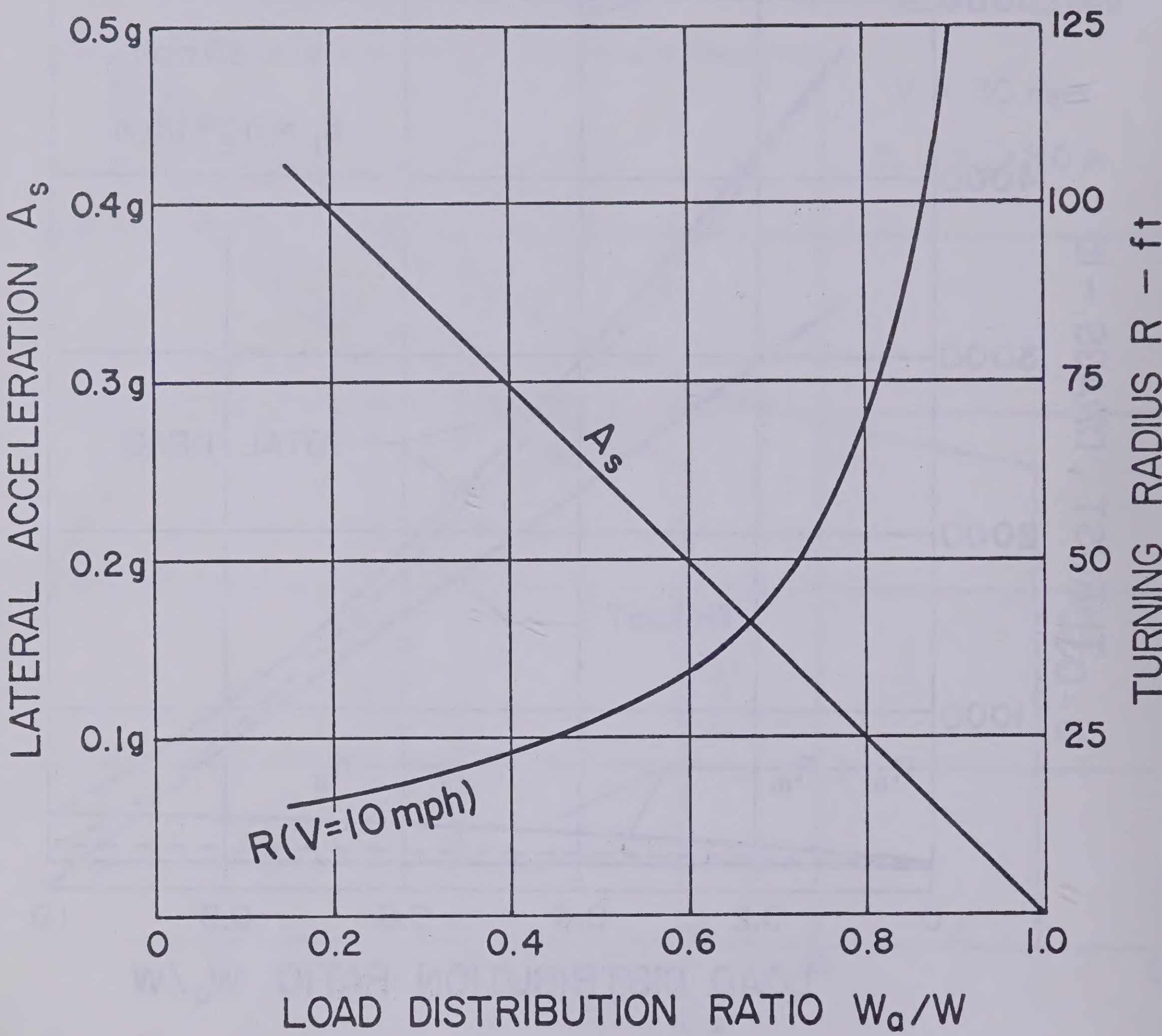

Figure 3 Variation of the maximum lateral acceleration and the minimum turning radius with load distribution of a hybrid vehicle in snow ($n = 1.0$, $K_c = 3.6$, $K_\varphi = 0.3$, $c = 0.1$ psi, $\varphi = \delta = 18^{\circ}$, $\gamma = 0.016$ lb/in^3, $N_\gamma = 1.24$, $N_c = 4.1$)